Two-dimensional crustal and upper-mantle velocity models from profile "Quartz", Russia

Igor Morozov, Werner Schueller, Elena Morozova, and Scott Smithson

Department of Geology and Geophysics, University of Wyoming, PO Box 3006, Laramie, WY, 82071-3006.

Grant F49620-94-1-0134, Sponsored by AFOSR

ABSTRACT

We develop two-dimensional (2-D) P-wave velocity models for the crust and for the upper mantle along the ultra-long Deep Seismic Sounding profile (DSS) "Quartz". Two-dimensional effects play a principal role in Lg propagation and are directly related to the problem of quantitative modeling of Lg and its use as a seismic discriminant. The use of DSS profiles provides us with unique opportunities to study large-scale propagation effects of various seismic phases, and especially Lg, across geological and tectonic boundaries. The results of this study have a direct relevance to the calibration of seismic discriminants.

To develop our 2-D crustal model, we use the data obtained using 28 chemical explosions along the north-western half of the profile. It is the first attempt of using these data after they have been digitized and obtained in the West. Applying a travel-time tomographic inversion method, we develop a velocity model and estimates of its resolution. Two important resolved features of the model are: 1) high velocity block at the base of the crust under the Baltic Shield, 2) crustal roots under the Ural Mountains.

Using the data from 2 nuclear explosions in the same part of the profile we develop a preliminary 2-D upper mantle P-wave velocity model. The model supports the conclusion of the roots under the Urals, and suggests a south-east dipping low-velocity zone in the upper mantle. The latter, however, is to be supported by the analysis of the data from the third nuclear shot, which is now in the processing stage.

As a result of this work, we will obtain a comprehensive 2-D model of the crust and of the uppermost mantle, will obtain better estimates of obtained resolution of geological features. This knowledge would provide better means of calibration of the amplitudes of Lg and other phases for their use in CTBT applications.

INTRODUCTION

We report our progress in the digitization, processing and interpretation of the data from the profile "Quartz". Profile "Quartz" (also known as Murmansk-Kizil profile) acquired in 1984-87 is a part of the unique Deep Seismic Sounding (DSS) program carried out in the USSR during the past 25-30 years. The profile spans 3950 km from northwestern Russia to central Asia, crossing six major tectonic provinces (e.g., Zonenshain et al., 1990). 3 nuclear explosions (PNEs) were recorded by over 330 3-component instruments spaced at 10-16 km. The same instruments were used with 42 chemical explosions which were recorded at 200-300 km offsets (Figure 1).

Recent descriptions of the data were given by Mechie et al. (1993) and Morozova et al. (1994); a detailed overview of the Soviet DSS program can be found in Ryaboy (1989).

Here we present two-dimensional velocity models for the crust and for the upper mantle (depth range 0-200 km). It is the first attempt since the data have been digitized and obtained in the West to perform an analysis of the chemical shot records, and to obtain a two-dimensional velocity model of the mantle. The models are derived from the analysis of the northwestern part of the profile (Figure 1). The rest of the data were recently obtained and are in the processing stage.

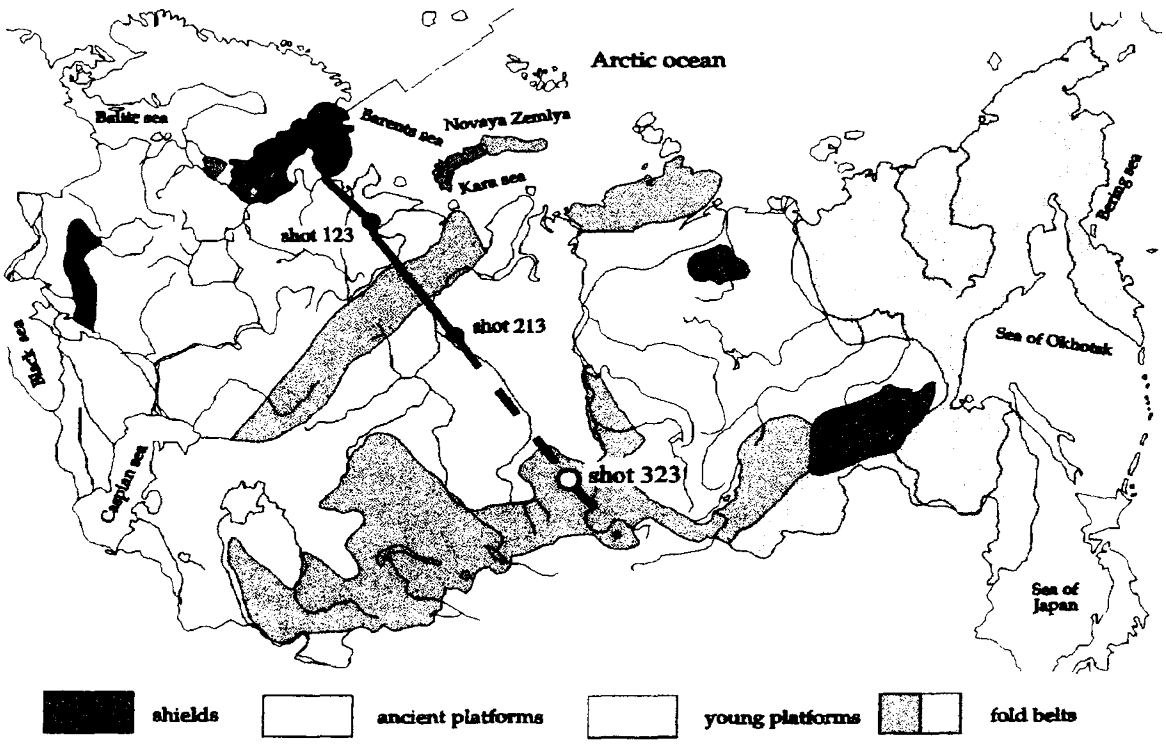

Figure 1. A generalized geologic map of the USSR. Profile "Quartz" is shown. *Solid line:* the part of the profile discussed in this paper. *Dashed line:* recently obtained remaining part of the profile.

OBJECTIVES

Ultra-long densely spaced DSS profiles using nuclear and chemical explosions provide unique opportunities to study wave propagation through complex lithospheric structures. This is particularly important in the context of the studies of the propagation of crustal-guided seismic phases, especially Lg. As we pointed out before (Morozova et al., 1994), existing crustal velocity models developed for the profile "Quartz" (Solodilov, 1994, personal communication) are not satisfactory for the purpose of the modeling of Lg propagation, which is recognized as one of the major issues for seismic calibration and monitoring. The profile also provides a substantial coverage of the upper mantle. One-dimensional models developed by several authors (Benz et al., 1992; Mechie et al., 1993) clearly show a number of features of prime importance (for example, prominent low-velocity zones), but are conceptually unacceptable for such a large-scale experiment (e.g. Ryaboy, 1989).

Our goals are first the development of comprehensive two-dimensional (2-D) velocity models for the crust and upper mantle using the data from both chemical and nuclear explosions. Our major concern is in the understanding of the obtained resolution of the velocity structure, and of its implications for the prediction of the propagation of seismic phases. The knowledge of the crustal P- and S- wave velocity is crucial the for understanding of Lg propagation of Lg. Depending on the scale of the problem, our specific objectives and corresponding methods of research (in approximate order of their priorities) are:

- To develop a <u>2-D P-wave crustal velocity model</u> and to estimate its spatial and velocity resolution using 2-D seismic travel-time tomography. Analysis of the To develop a <u>2-D P-wave crustal velocity model</u> and to estimate its spatial and resolution obtained and a comparison to earlier models of the crustal velocity structure.

- To obtain a <u>2-D P- and S-wave velocity model of the upper mantle</u> using the data from chemical shots for the uppermost part of the mantle, and 3 nuclear shots sampling the depth range of 0-400 km.

- To measure true <u>amplitudes of seismic phases</u> (especially those of P_n, S_n, L_g) along the profile, incorporating them into the travel-time inversion. To study their <u>amplitude ratios as potential seismic discriminants</u>.

- To establish constraints on the <u>2-D S-wave crustal velocity structure</u>.

- To investigate the possibility of using receiver function analysis to study <u>converted phases</u> in order to constrain S-wave velocity structure of the crust.

- To develop methods of analysis for the application to <u>the remaining part of the profile</u>.

- To <u>model L_g wave propagation</u> across laterally variable geological structures; to study the effects of the crustal P- and S- wave velocity structure on L_g wave propagation. Possibly to incorporate Lg into the travel-time crustal velocity inversion.

- As an integrating result, <u>calibration of regional seismic event discriminants</u>.

We have reported before our progress in the digitization, in basic processing, and in the measurement of vector and scalar amplitudes of the data from profile "Quartz" (Morozova et al., 1994, 1995). In this work we will discuss only problems related to the two-dimensional travel-time inversion of the data at two different scales - crustal, using the chemical shots, and upper mantle - using PNEs.

RESEARCH ACCOMPLISHED

2-D tomographic crustal velocity model

In the earlier velocity models developed in GEON[1] one of the most important processing steps was the "velocity filtering" (Ryaboy, 1989; Katz and Shubik, 1977), which is a nonlinear event-enhancing procedure. To our knowledge, the performance of the procedure in terms of the generation of spurious events has not been studied at all. The P-wave crustal velocity structure developed in GEON shows a large number of vertical and lateral velocity contrasts, with faults offsetting the Moho boundary (Figure 2). Such contrasts, if they are real, would greatly affect the propagation of crustal-guided waves and would be most important for our interpretation and modeling of Lg phase. A reliable crustal model is also necessary for the resolution of 2-D upper mantle structure. Therefore, a solution of problems of robust event detection and a critical reinterpretation of the crustal and upper mantle velocity models will be of crucial importance for this project. One of the immediate purposes of our study is to obtain a relevant P- and S-wave velocity model and to estimate its resolution. Seismic tomography provides one of the possible means to determine such a model.

A linearized tomographic inversion method based on the algorithm by White (1989) was applied to a part of the dataset including 28 chemical and 2 nuclear explosions at the northwestern part of the profile (Figure 1). The P-wave velocity model was defined on a uniform rectangular grid with horizontal spacing of the nodes 50 km and vertical spacing of 3 km. The values of velocity at the nodes were iteratively updated using a variant of conjugate gradient method (LSQR, Page and Saunders, 1982). LSQR method provides rapid solving of the sparse and large linear system of equations (common dimension of the system is about $10^3 \times 10^3$ elements. The disadvantage of this technique is in not providing an estimate for the model resolution.

A realistic starting model is important to generate a convergent solution. For our starting model we used a velocity/interface model obtained from a simplified and smoothed model produced in GEON. The data (travel time) root-mean-square (RMS) misfit for this model was 588 ms.

The first two iterations determined the uppermost crustal structure to the depth of about 9 km. Only rays refracted in the upper crust were used. No reflections from the top

[1] GEON - Center for Regional Geophysical and Geoecological Research (formerly the Special Geophysical Expedition) in Moscow, Russia, - the organization which had been in charge of the acquisitio, archiving, and processing of the data.

of the basement in the southern and central part of the study area could be identified. During the next iterations the uppermost velocity structure was maintained fixed, and P-wave refractions (Pg and Pn) and Moho reflections were included into the inversion. The velocities in the middle and lower crust, velocities in the uppermost mantle, and the depth of the Moho were obtained. The resulting velocity model is shown in Figure 2. Ray coverage (for refracted rays only) and the final travel time fit are shown in Figure 3. The RMS data misfit for this model was reduced to 252 ms, and could not be reduced further without introducing unrealistic model features. This misfit is close to the travel time picking errors for deeper events.

The most significant features of the resulting crustal model are the presence of the high velocity block at the base of the Baltic Shield and the crustal root beneath the Uralian foldbelt. The evidence for the root is quite clear. The model shows the depth of the Moho at about 46 km corresponding to low crustal velocities of 7.1 km/s and upper mantle velocities of 8.1 km.

The southeastern part of the profile is characterized by a thick sedimentary basin with velocities around 2.5-3.4 km/s and depth varying from 2 to 4.5 km. Crustal

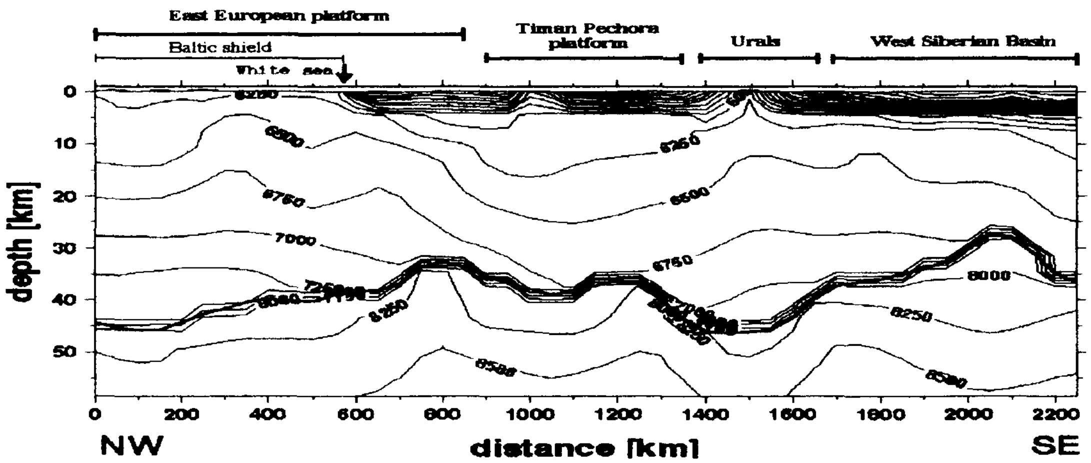

Figure 2. Crustal and uppermost mantle P-wave velocity model obtained using 2-D travel-time tomographic inversion.

basement velocities are below 6.9 km/s, upper mantle velocities range from 7.9 to 8.1 km/s. The tomographic inversion shows a prominent uplift in the Moho at about 2100 km along the profile. This feature is not supported by current geologic models and is not present in earlier interpretations. At present it is constrained only by three southern shot records. Additional data from the rest of the profile should allow us to verify the validity of this feature.

Following White (1989), we use singular value decomposition (SVD) to determine the resolution of the obtained velocity model. The resolution matrix $\mathbf{R} = \mathbf{V}_p \mathbf{V}_p^T$ is obtained from the SVD decomposition of the linear system $\mathbf{A} = \mathbf{U}\Lambda\mathbf{V}^T$, with $\mathbf{U}$ and $\mathbf{V}$ being the matrices of left and right singular vectors, and Λ a diagonal matrix of singular values of $\mathbf{A}$. The subscript p indicates the separation of the subspace corresponding to

non-zero singular values. A traditional way to illustrate the resolution to plot diagonal elements of the matrix **R** (top of Figure 4).

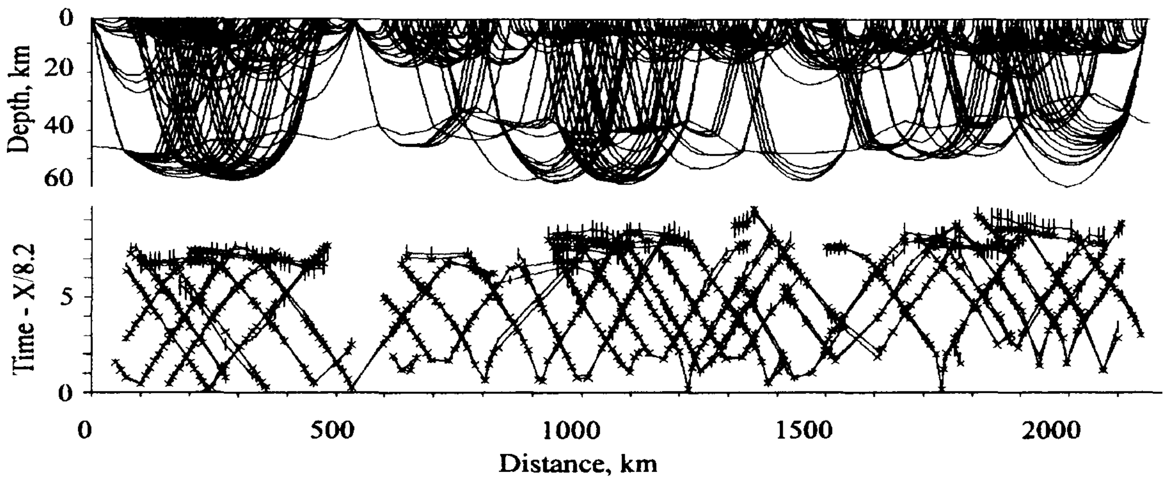

Figure 3. *Top:* refracted rays in the final tomographic velocity model. *Bottom:* travel time fit. The RMS misfit is 252 ms. Reduction velocity is 8.2 km/s.

The resulting resolution structure shows values near 1.0 in the upper crust along the northern and central part of the profile. The edges of the model and most areas of the upper mantle are only poorly resolved. The resolution is highest at the top 20 km of the and near the Moho (Figure 4). The latter is apparently due to additional coverage provided by the reflected waves.

Under the assumption that the uncertainties in the picked travel times are uncorrelated with uniform variance δ, the velocity model covariance matrix can be calculated as $\mathrm{cov}(v) = \delta \mathbf{V}_p \Lambda_p^{-2} \mathbf{V}_p^T$. A plot of the velocity variance is shown at the bottom of Figure 4. This plot represents the estimated uncertainties in model velocities. These uncertainties, however, are interrelated with the uncertainties of the locations of various spatial features (e.g., Moho). This dependence does not lend itself easily to graphical representation, and thus the problem of the evaluation of the full spatial and velocity resolution is yet to be solved.

Preliminary 2-D upper mantle model from ray tracing

We used 2-D ray tracing to obtain a comprehensive upper mantle velocity structure along our part of the profile. For the crustal model, we used the same smoothed model that we used as a starting model for tomography. Adjusting mantle velocities to achieve a fit of the picked travel times of Pn and of the reflections from the top of the low-velocity zone (LVZ), we obtained a velocity model shown in Figure 5. In our inversion we intentionally tried to constrain only large-scale structures within the mantle. Below the LVZ our model is essentially one-dimensional, since this depth range is sampled only by the waves from the middle PNE (213). Two important 2-D features constrained by our model are: 1) the LVZ is dipping in a SE direction; 2) the ray tracing supports the relief of the Moho and lower upper-mantle velocities under the Ural Mountains obtained by the

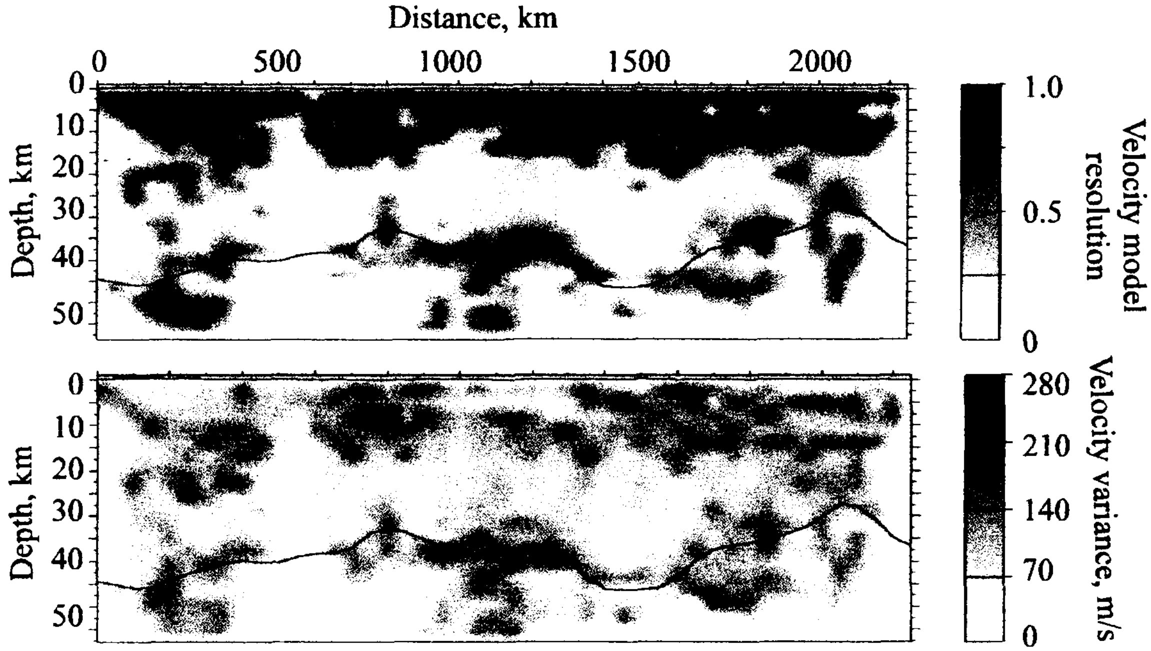

Figure 4. *Top:* diagonal elements of the velocity resolution matrix **R**. *Bottom:* estimated velocity variance. Location of the Moho interface obtained from tomographic inversion is also shown. Note that small velocity variance at the lower crust under the White Sea region (distance about 550 km) is rather due to insufficient ray coverage and low resolution.

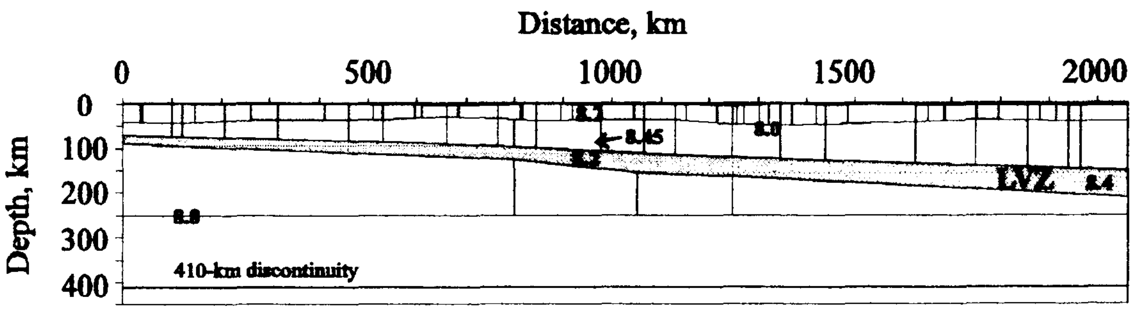

Figure 5. A preliminary (based on the data from 2 PNEs) upper-mantle velocity model. Note the roots under the Urals and the dipping in SE direction low-velocity zone in the upper mantle. Some P-wave velocity values are labeled in km/s.

tomographic inversion. These features can be related to the presence of roots under the Urals. We observe remarkable lateral variations of the P-wave velocities under the Moho boundary near the Urals: from about 8.2 km/s under the Timan Belt to the lowest for this profile values of 8.05-8.1 km/s under the Urals, and to higher velocities of 8.3-8.35 km/s under the West Siberian Platform.

Receiver function analysis: converted phases

The boundaries obtained in P-wave tomographic inversion may be completely different from the interfaces producing P-S conversions, which play a principal role in the formation of Lg. Careful examination of the first breaks of the "Quartz" data records shows that strong P-S converted phases (clearly observed in the horizontal components) are following the first breaks. To evaluate the time delays of these converted phases, we calculated receiver functions by rotating the horizontal components to their maximum amplitude and deconvolving the result from the vertical component (Figure 6). We use the receiver function normalization scheme proposed by Ammon (1991). Although the receiver functions are comparatively narrow-band, corrupted by noise, and difficult to interpret, three observations can be made: 1) there are no observable P-S conversions for the receivers located on the Baltic Shield; 2) the general patterns of the receiver function gathers are similar for shots 123 and 213 and follow the variations in the thickness of sedimentary rocks; 3) we do not see any conversions on the Moho: the delays of 0,3-1 s are smaller than expected for P-S conversions (3-4 s) on the Moho boundary.

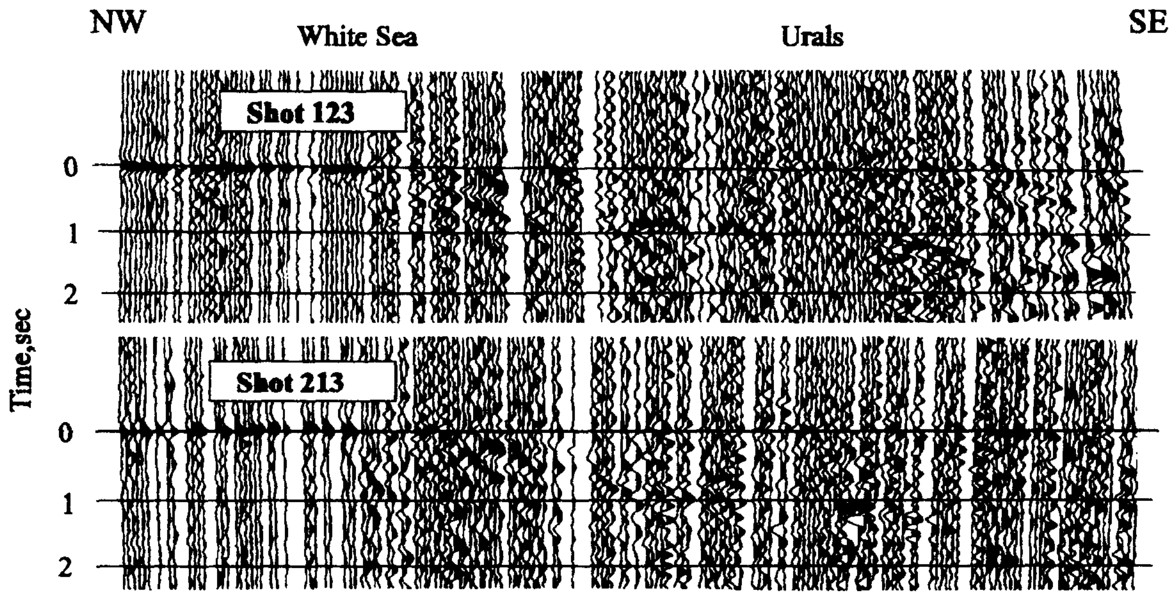

Figure 6. Receiver functions calculated for shots 123 (northern PNE) and 213 (middle PNE). Note the absence of conversions in the Baltic Shield area (left side of the gathers) and the correspondence of the pattern of receiver functions to the thickness of sediments (compare to Figure 2).

CONCLUSIONS AND RECOMMENDATIONS

Based on 600-sec digitization and processing of the data from long-range DSS profile "Quartz" we are able to detect a number of seismic phases refracted and reflected within the upper mantle and to analyze the propagation of crustal-guided waves (Pg and Lg) throughout the entire distance range (2000 km at present). Our analysis of the data shows that:

- The LVZ observed in the upper mantle before is dipping in a SE direction and is located at depths of about 100 km under Kola Peninsula and 200 km under the West Siberian Platform. The thickness of the LVZ increases from 20 km at the NW end of the profile to about 40 km at the SE end.
- Dipping Moho boundary relief and lower mantle velocities under the Urals can be associated with the roots of Ural foldbelt.
- as we pointed out before (Morozova et al., 1994) Lg phase is comparatively weak in the northern and middle PNE records. A preliminary examination of the data from the southern PNE shows that Lg phase is very prominent in these records, at least on the West Siberian basin.
- The Lg phase is much weaker than recorded on the Baltic Shield and appears to be blocked by Ural Mountains.

We observed P-S conversions on the top of the basement. These converted waves, however, cannot be Our work with these data is not, however, complete. Our major concern in future work is related to the improvement of the crustal and uppermost mantle P- and S-wave velocity models. The most important steps we will take are:

- we will complete the basic processing of the rest of the data (southern PNE, far-offset parts of the other 2 PNEs, and 12 chemical shots).
- we will complete our tomographic inversion of the crustal velocity structure.
- constraints of the S-wave velocity of the crust will be obtained from S-wave phases observed in chemical shot records, and possibly from the receiver function analysis.
- responsible for complex first break signatures.
- we will perform joint amplitude analysis of all three PNE records. The records from the southern PNE would yield new insight into the Lg blockage under Urals which we suggested before.
- 2-D modeling will be carried out for the entire “Quartz” profile, including the third PNE. This would strengthen our conclusions about the thickness and the shape of LVZ in the upper mantle.
- amplitude information needs to be included into the 2-D inversion of the upper mantle. This is necessary for the validation of the upper mantle velocity model (Ryaboy, 1989), and for the analysis of amplitude ratios, as seismic discriminants.
- based on the above, we will be able to perform a quantitative analysis and modeling of Lg phase propagation across the boundaries of various geological structures.

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